

Technologies for High Performance and Reliability of Geothermal Power Plant

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ABSTRACT

The origin of Mitsubishi's geothermal steam turbine technology dates back to 1951 with one small 30kW unit. 16 years later, in 1967, our first commercial geothermal steam turbine commenced operation at the Otake Geothermal Power Plant of Kyusyu Electric Power Co., Inc. Since the beginning of the 1960s, we have conducted many testing at geothermal fields and laboratory in our Nagasaki R & C center and developed many kinds of equipment or system for higher performance and reliability of geothermal turbine or power plant. In this paper, those technologies supporting high performance and reliability of our supplied geothermal power plant and steam turbine are introduced.

1. INTRODUCTION

In May 2008, Mitsubishi received an order for five units of 45,000kW geothermal power plants from Iceland and thereby reached our first triple-digit geothermal steam turbine order. With these five units, the total output of geothermal steam turbines or plant awarded to our company exceeded 3,000 MW, as indicated in Figure 1.

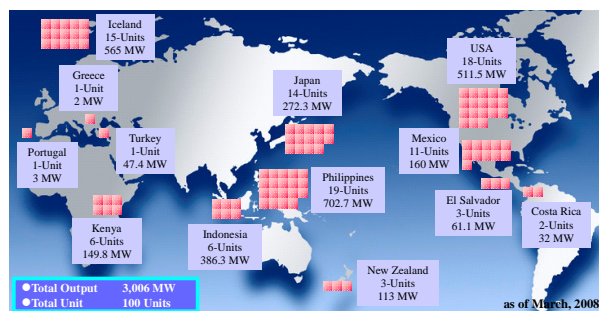


Figure 1: Worldwide distribution of plants.

Features of geothermal power plants are;

- Geothermal power plant performance is affected by production well pressure-flow characteristics and by atmospheric wet bulb temperature which are different at each steam field or project site. Therefore, optimization for plant cycle, main steam pressure, wet bulb temperature and condenser pressure needs to be performed for each project to maximize plant net output for a long time.
- Geothermal brine or steam contains higher concentration of impurities and non-condensable gas (NCG) compared with conventional thermal power plants. Harmful impurities or NCG causes scaling and corrosion related problems. Technologies for

reliability of the plant in such severe circumstance are very important to maintain required availability.

- Steam at the turbine inlet is at saturated condition and wetness in the turbine is higher than in the case of conventional thermal steam turbines. Higher wetness causes erosion in the turbine internals and makes the turbine efficiency lower. So, apparatus to remove the wetness from the turbine is also very important.

We are a manufacturer of geothermal power plant equipment such as turbine, condenser and plant control system. At the same time we are also a total engineering company for geothermal power plant and able to carry out plant optimization and plant performance design. Thus we have been able to supply geothermal power plants that best match the geothermal resource, atmospheric conditions and customer's requirements.

2. PLANT OPTIMIZATION

We perform plant optimization at the bidding stage to offer the geothermal power plant with maximum output at low cost under given conditions and requirements.

2.1 Cycle selection

Refer to Figure 2 for process diagrams.

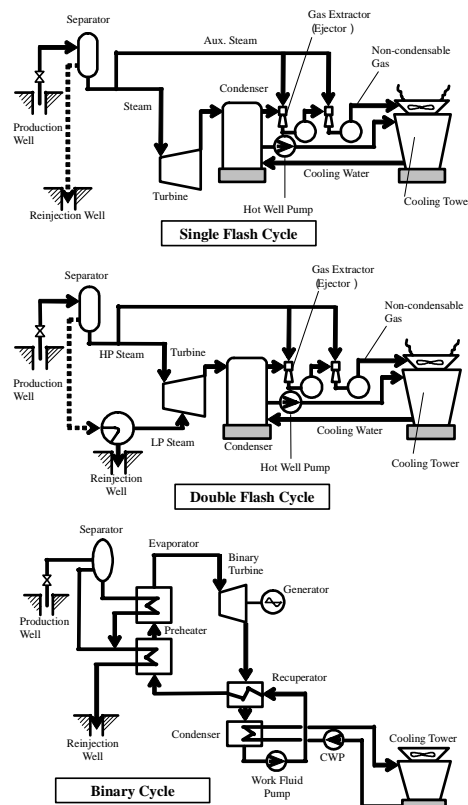


Figure 2 : Process Diagram

Cycles for geothermal power plant are classified into Binary cycle and Flash cycle. Binary cycle usually uses low boiling temperature media as a working fluid. Binary cycle is applied to the plant in case that bottom hole temperature of the production well is low. Even in the case with low bottom hole temperature, flash cycle is also applicable with low steam pressure selection, and plant performance of the low pressure flash cycle is comparatively higher than the binary cycle. However, the advantage of the binary cycle is that pressure in the whole system including turbine inlet and condenser is higher than the case of the flash cycle and the size of equipment and piping in binary cycle power plants with low bottom hole temperature resource is smaller than in the case of flash cycle.

Flash cycle is classified into single-flash cycle and multiple-flash cycle.

In the single-flash cycle, hot water from a separator is reinjected into the ground through reinjection wells.

Double-flash or triple-flash cycle is usually applied and only double-flash cycle is discussed in this paper. In double-flash cycle, hot water from a high pressure (HP) separator is led to a low pressure (LP) separator and the secondary steam generated when the hot water is flashed at pressure lower than the HP separator is led to an intermediate stage of the steam turbine to contribute additional power generation. Roughly speaking, a double-flash cycle plant can generate 20% additional power compared to a single-flash cycle, although additional costs for the secondary steam generation is approximately 5% higher than the single-flash cycle. In the meantime, the temperature of hot water injected into the reinjection wells is lower in the double-flash cycle and attention needs to be paid to the scaling problem in the reinjection lines or wells. Secondary pressure needs to be selected carefully or chemical injection into reinjection lines will be considered to prevent scaling based on the concentration of impurities such as silica and chloride in the brine.

2.2 Main steam pressure

Refer to Figure 3 for main steam pressure optimization.

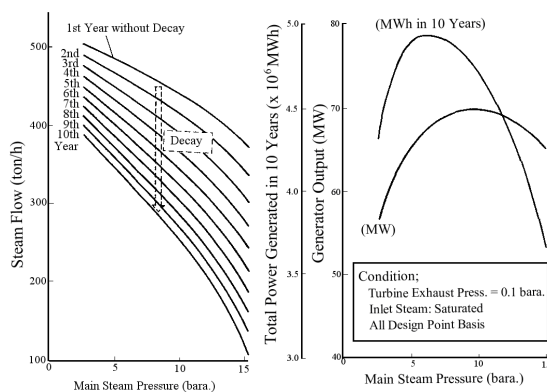


Figure 3: Main Steam Pressure Optimization

Generator output is given by the following equation.

$$P = G \times (H1 - H2) \times \frac{\eta}{3600}$$

P: Generator out put (kW)

G: Steam flow (kg/hr)

H1: Turbine inlet enthalpy(kJ/kg)

H2: Turbine exhaust enthalpy (kJ/kg)

H1-H2: Isentropic heat drop in a turbine

η : Turbine-generator efficiency

As can be seen from this equation, steam flow rate and isentropic heat drop in a turbine are conflicting factors that increase or decrease generator output when main steam pressure is changed. Therefore, it is seen that there is an optimum main steam pressure to maximize the generator output. It should be noted that the optimized pressure based on only the current production well characteristics is different from the optimized pressure based on both current characteristics and decayed characteristics that the well will experience in the future. Usually, optimized pressure when decayed future characteristic is also considered is lower than the pressure optimized based on only current characteristic. If you can determine the actual decay in production wells after a long period of operation, you can adjust the main steam pressure to maximize generator output to a certain extent with your production wells, by replacing first stage nozzles and/or moving blades of the steam turbine.

Higher main steam pressure causes higher wetness at the turbine exhaust and therefore, after you have selected optimum pressure, you should check that wetness at the turbine exhaust is within an allowable range in view of the erosion problem in the last stage moving blades.

2.3 Condenser pressure

Refer to Figure 4 for condenser pressure optimization.

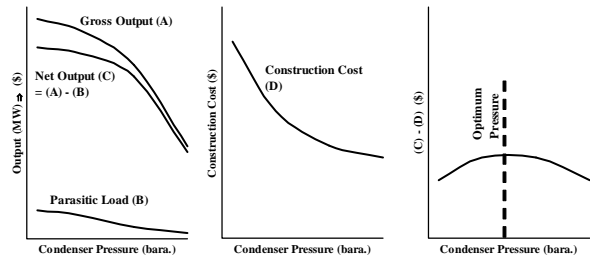


Figure 4: Condenser Pressure Optimization

In case lower condenser pressure is selected, each factor varies as follows.

- Heat drop in turbine and generator output increase
- Motive steam and parasitic load for NCG extraction system increases and generator output decreases and a larger NCG extraction system is required
- Higher cooling water rate or lower cooling water temperature is required and this means that larger cooling water system including cooling tower, hotwell pumps, cooling water pipe or condenser is required.

Taking these variations into consideration, income through net output based on generator output and parasitic load and costs for equipment and construction work need to be evaluated at the same time and the optimum condenser pressure should be found.

3. EQUIPMENT PERFORMANCE

The next step in an optimization study is to design high efficiency equipment such as steam turbine, generator, condenser, cooling tower and NCG extraction system.

In this section, measures to improve turbine efficiency are discussed.

Three-dimensional design of impulse blades is applied to reduce secondary loss and consequently improve stage efficiency by 1.5~2%. The optimum length of the last stage blades and the optimum number of turbine exhaust need to be selected to minimize leaving loss at the last stage rotational blades exit. Refer to Figure 5 for leaving loss characteristic. The drain catcher at each stage reduces wetness of steam and improve the turbine efficiency and this apparatus decreases erosion rate of the leading edge of the last stage rotational blade.

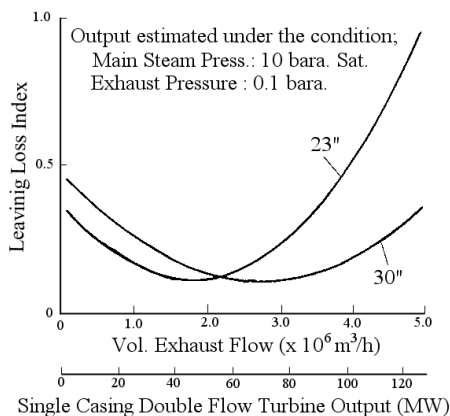


Figure 5: Optimum Last Stage Blade Length

4. RELIABILITY

4.1 Material selection

Good material selection is required so that damage such as stress corrosion cracking and corrosion fatigue is effectively prevented and inexpensive material can be applied to the appropriate part or area. To realize good material selection, material tests have been conducted in 12 steam fields over the world. The tests were conducted to check characteristics of corrosion rate, stress corrosion cracking and corrosion fatigue of materials used for geothermal steam turbine. Based on extensive test results, our material selection procedure has been established.

Corrosion rate test results are reflected in the design corrosion allowance. The materials for high stress parts such as the rotor and rotational blades are selected based on the results from stress corrosion cracking tests, corrosion fatigue tests in geothermal steam in addition to usual mechanical properties such as tensile strength. Fatigue strength in geothermal steam is lower than that in clean air and this degradation in geothermal steam should be correctly incorporated into vibration stress analysis of rotational blades. Table 1 shows our typical material selection for geothermal steam turbines.

In cases where steam turbine rotors have damage such as stress corrosion cracking, welding repair is required in some cases. We developed a welding procedure for turbine rotors made of CrMoV or 12Cr-5Ni using 12Cr-5Ni

welding rod material. We confirmed that the welded material and heat affected zone have good mechanical properties and the strength is higher than the specification of the rotor forging, and strength in geothermal steam against stress corrosion cracking and corrosion fatigue is within the allowable range. This welding repair procedure using 12Cr-5Ni welding rod material can be applied to the blade groove area where the stress level is highest in the rotor.

4.2 Steam purity

Water entrainment into geothermal steam at a separator outlet contains high concentration of harmful impurities such as silica or chloride, so water entrainment should be minimized. Therefore a high efficiency steam separator and flasher were developed to protect steam turbines from scaling problems and corrosion related damage. The vertical type of cyclone separator is usually applied and the horizontal type of flasher with internal cluster is applied to secondary steam in case of double-flash systems. In case we could not meet the main steam purity required by the steam turbine with a single-stage separator or flasher, a scrubber system composed of water injection and additional separator is applied.

4.3 Measures against scaling in turbine first stage nozzle

It is most important to monitor the scaling condition at the first stage nozzle by checking the “first stage nozzle inlet pressure/main steam flow rate”, and if this parameter increases by 15% compared with clean conditions just after initial steam admission, then scaling should be removed.

Scale can be removed mechanically after disassembling the upper casing or rotor or can be removed by clean water injection into the main steam during full load operation.

4.4 Welding overlay and thermal spraying for turbine rotor

Welding overlay and thermal spraying for the turbine rotor gland area were developed to protect the rotor from erosion-corrosion. Inconel625 is used for both welding overlay and thermal spraying.

4.5 Non destructive testing for geothermal steam turbine

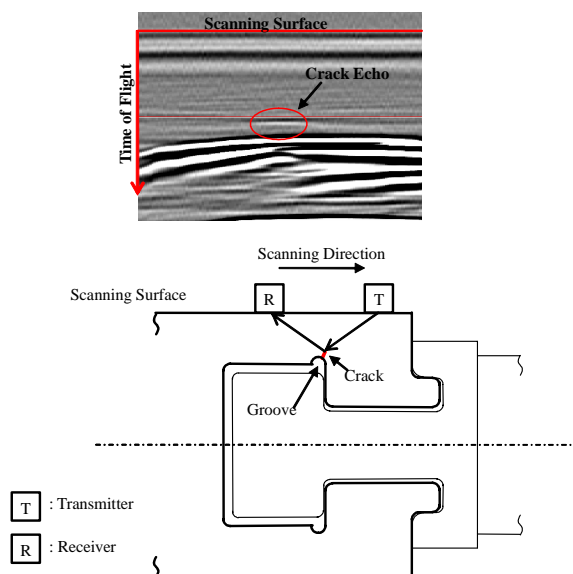
Magnetic particle test and penetration test are usually applied to check if there are defects in turbine parts during overhaul. The areas under very severe condition in view of stress and corrosiveness in geothermal steam turbine are;

- (1) The corner of blade groove at first stage and second stage
- (2) Disc root at first and second stage

Specialized TOFD (Time of Flight Diffraction) method was developed in order to detect the defect in the blade groove without removing rotational blades from the rotor. If the detected crack is small enough, it is possible to remove the crack by skin cut and welding repair is not required. Refer to Figure 6 for TOFD method applied to blade groove.

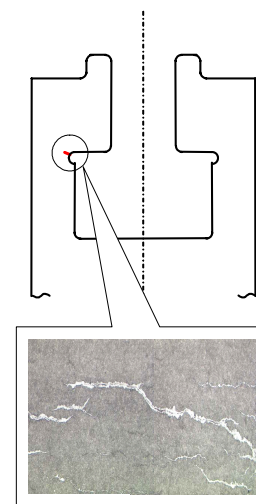
Table 1: Typical Material Selection for Geothermal Steam Turbine

| | Corrosiveness | |
|---------------------------------------|--|--|
| | Usual | Severe |
| Turbine Casing | Carbon Steel | |
| Turbine Rotor | Low Sulfur CrMoV | 12Cr-5Ni |
| Rotor Gland Area | Inconel 625 Thermal Splaying | Inconel 625 Welding Overlay |
| Rotational Blade (1st Stage) | 17-4PH | Titanium |
| Rotational Blade (Intermediate Stage) | 12Cr | 12Cr / 17-4PH |
| Rotational Blade (Last 2~3 Stages) | 17-4PH | |
| Stationary Blade | 12Cr for short blades and 18Cr-8Ni for long blades | |
| Diaphragm | Carbon Steel | Carbon Steel with SS316L overlay for limited area. |

**Figure 6: TOFD for Blade Groove**

Replication method specialized to detect the defect such as corrosion in grain boundary or small size of stress corrosion cracking at stress riser such as disc root or blade groove was developed. If the crack size is small enough, skin cut is applicable to remove the defect.

Refer to Figure 7 for a sample of replication.

**Figure 7: Replication of Crack in Blade Groove**

5. CONCLUSION

As introduced in this paper, we have developed extensive technologies for high performance and reliability of geothermal power plants. We believe that the plant owner's professional maintenance and technologies developed by us are supporting high availability of our supplied geothermal power plants as listed in Table 2.

Table 2 : Availability of Geothermal Power Plants

| Plant | Output (MW) | Operation Date | Availability* in 2007 (%) |
|---------------|-------------|----------------|---------------------------|
| Otake | 13 | 1967 | 95.6 |
| Onuma | 10 | 1974 | 96.2 |
| Hatchobaru #1 | 55 | 1977 | 98.1 |
| Hatchobaru #2 | 55 | 1990 | 95.1 |
| Sumikawa | 50 | 1995 | 98.6 |
| Yamagawa | 30 | 1995 | 95.4 |
| Takigami | 25 | 1996 | 100 |
| Ogiri | 30 | 1996 | 94.5 |

* Availability = Operating days / Calendar days